Electro-Optical Effects in Liquid Crystals

L.M. Blinov
Calabria University

I. General picture
II. Basic effects (nematics, cholesterics, smectics)
III. Frederiks transition: past and present
IV. Helix unwinding: pro and contra
V. Electro-optics of a spatial soliton: glance in future

For more details and earlier achievements see
L.M. Blinov, V.G. Chigrinov, **Electrooptic Effects in Liquid Crystal Materials,** Springer, 1996, p.464, figs. 221.

I. General picture

1. Why liquid crystals?

Gases, liquids and isotropic solids (e.g. polymers)

a) Electric field induced shift and splitting of spectral lines (Stark, 1913)

$$\Delta W = \Delta p E + \Delta \alpha E^2$$

and correspondent change in absorption and refraction (Kramers-Kronig)

b) Electric field induced reorientation of anisotropic molecules (Kerr, 1875)

In both cases: quadratic-in-field EOE: $$\Delta n \propto kE^2$$

Solid systems with polar symmetry such as polar crystals (Pockels. 1984), ferroelectrics (Valašek, 1921), or poled polymers called electrets

In this case: linear-in-field EOE $$\Delta n \propto \beta E$$

The key parameter is $\Delta n(E)$

Liquid crystals: what is new?

Large Δn? No, some molecular crystals have Δn even larger, up to 0.5.
Low viscosity? No, many polar liquids have smaller viscosity (e.g., nitrobenzene)
New effect? No, the field induced molecular reorientation like in the Kerr effect

$$Q = S(n_i n_j - 1/3)$$

Really new is
the new type of molecular ordering in a liquid state.

Now the electric field can reorient the director (optical axis, i.e. "direction of Δn")

In the bulk, the reorientation of all molecules at once does not require energy (Goldstone mode). In a thin cell, the reorientation of almost all molecules at once requires only low energy (due to small Frank elastic moduli in the liquid state)

The EOE is strong even in thin cells at low voltages $$I = I_0 \sin^2 \beta \sin^2 \frac{2\pi d \langle \Delta n \rangle}{\lambda}$$

The switching times in thin cells are sufficiently short (ms) $$\tau \approx \frac{\gamma d^2}{K\pi^2} \text{ or } \approx \frac{\gamma}{PE}$$

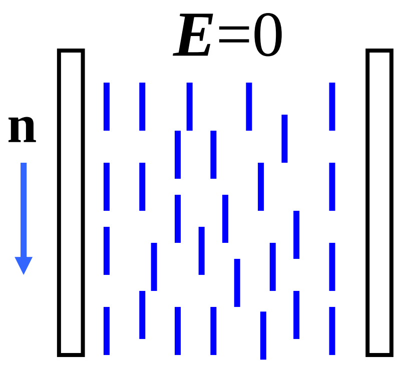
LCs are materials for thin film devices with many pixels, like displays, SLM, etc

2. A principle of free energy minimum (with bulk + surface terms)

$$F = F_V + F_S = \int_V (g_{elast} + g_{field})dV + F_S$$

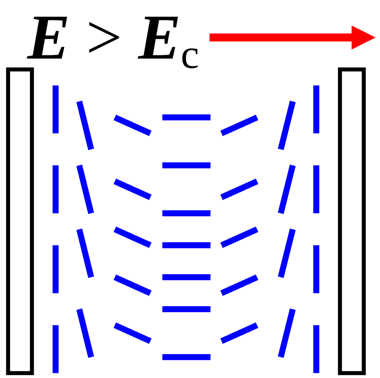
Density of elastic energy with splay, twist and bend terms (Frank):

$$g_{elast} = K_1(div\mathbf{n})^2 + K_2(\mathbf{n}\,curl\,\mathbf{n} + q_0)^2 + K_3(\mathbf{n}\times curl\,\mathbf{n})^2$$



Density of electric energy (quadratic and linear in field):

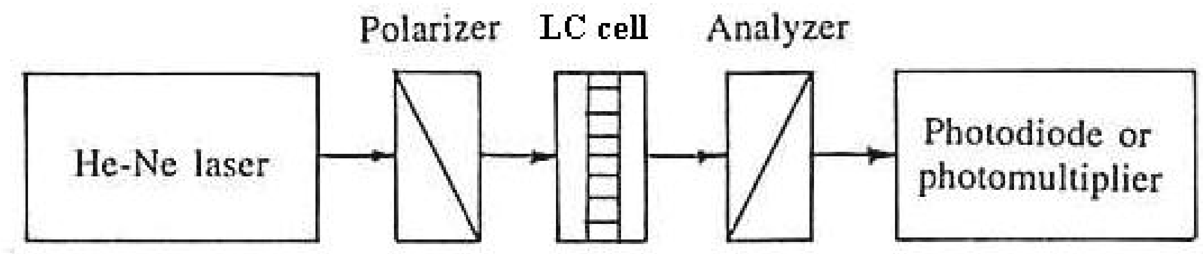
$$g^{Q}_{field} = -\frac{\mathbf{DE}}{8\pi} = -\frac{\varepsilon_\perp E^2}{8\pi} - \frac{\varepsilon_a(\mathbf{E}\cdot\mathbf{n})^2}{8\pi}$$



$$g^{L}_{field} = -\mathbf{P}\cdot\mathbf{E}, \quad \mathbf{P} = \mathbf{P}_{spont} \quad \text{or} \quad \mathbf{P}_{flex}$$

$$\mathbf{P}_{flex} = e_{splay}\mathbf{n}\cdot div\mathbf{n} + e_{bend}(\mathbf{n}\times curl\,\mathbf{n})$$

3. Electro-optical effects (general)



Planar structures:
(i) Transmission or reflection modes,
(ii) any sources, white or monochromatic,
(ii) any field, longitudinal or in-plane with interdigitated electrodes

For waveguiding geometry: come to the next lecture!

In any case we have the same list of effects:

Field controlled birefringence
Field controlled absorption positive (color) or negative (lasing)
Field controlled scattering or difraction

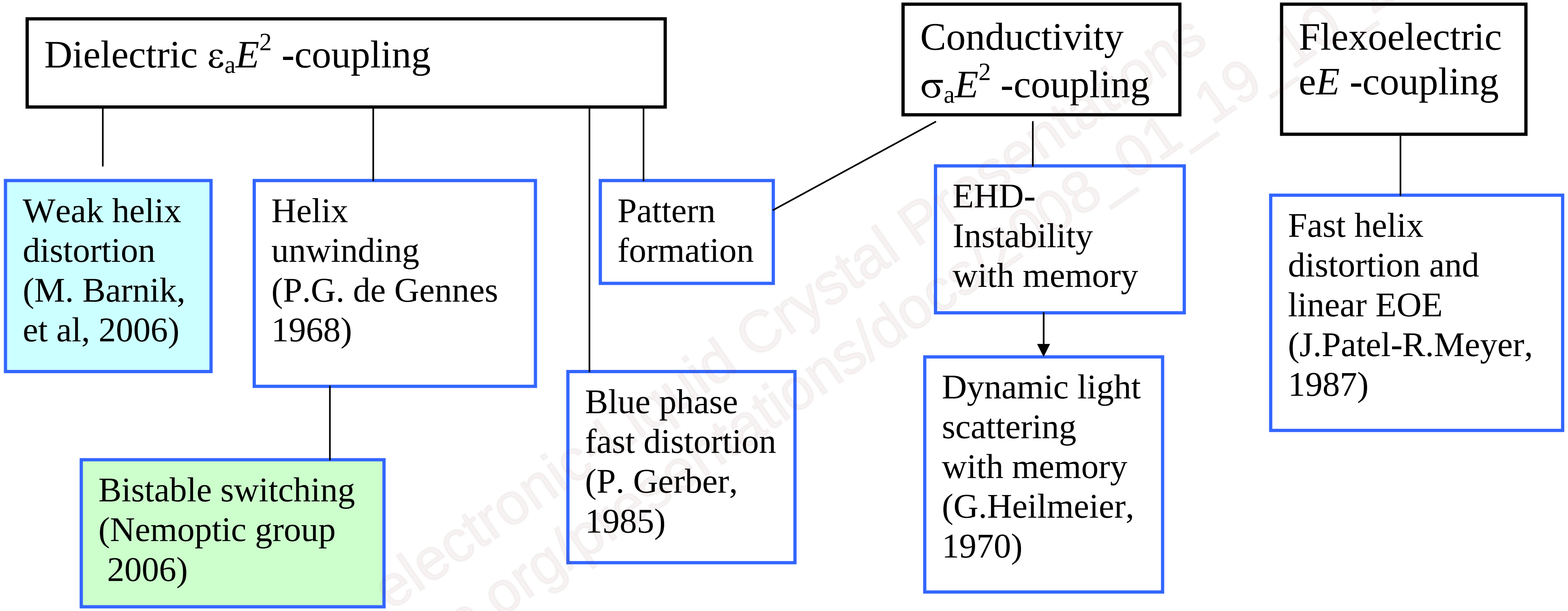
II.1 Basic EOE: Nematics

First observations: I. Bjornstahl (1918)

- **Dielectric $\varepsilon_a E^2$ -coupling**
  - Frederiks transition and reorientation (V. Frederiks, 1929)
    - Guest-Host effect G. Heilmeier et al 1968) Phase modulation (N.Basov et al, 1972)
      - Dual frequency addressing
  - Break of anchoring & bistability (J.Nehring et al, 1976)
  - Twist and supertwist effects (M.Schadt-W.Helfrich, 1971)
- **Conductivity $\sigma_a E^2$ -coupling**
  - EHD-Instability
    - Dynamic light scattering (V. Tsvetkov, 1935), G. Heilmeier et al, 1968)
- **Flexoelectric eE -coupling**
  - Polarization & director reorientation (R.Meyer' 1968)
  - Flex-Bistability G.Durand et al (1992)
  - Static domain instability with variable period L.Vistin' (1970)

The Frederiks transition and corresponding EOE (twist-effect, phase modulation, guest-host effect, etc.) are the basic effects for displays, SLM and NLO

II.2 Basic EOE: Cholesterics



For applications the most important are bistable switching and weak helix distortion (dielectric and flexoelectric)

II.3 Basic EOE: Smectics

Ferroelectric SmC* and A* phases

- In-plane bistable director switching (N.Clark-S.Lagerwall, 1980)
  - V-shape hysteresis-free effect (A.Fukuda, 1996)
- Deformed helix linear effect B.Ostrovsky et al, 1978)
- Electro-clinic effect in SmA* (S.Garoff-R.Meyer, 1979)

Antiferroelectric & Ferrielectric phases

- Multiple field-induced transitions (A.Fukuda et al, 1988)

Polar achiral smectics

- Piezo-hysteresis in “polyphilics” F.Tournilhac, 1992)
  - Linear EOE in “bananas” (H.Takezoe et al, 1996)

In-plane FLC switching has found application in displays and fast SLM

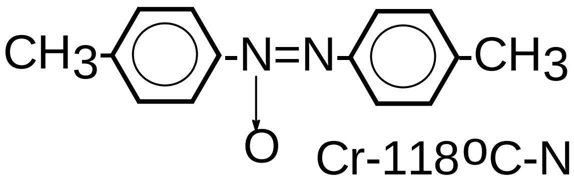
Two dreams:

(i) polar nematics for linear EOE

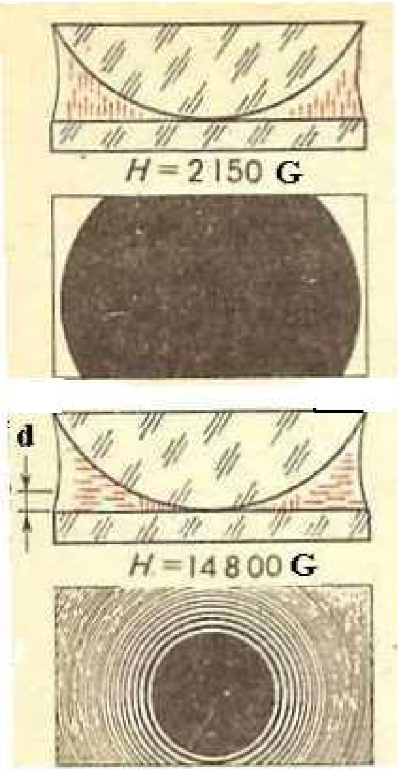
(ii) biaxial nematic for fast quadratic EOE

III. *Frederiks transition (1929)*

-*p,p'*-azoxyanisol (PAA), homeotropic



Cr-118^{o}C-N-135^{o}C-Iso



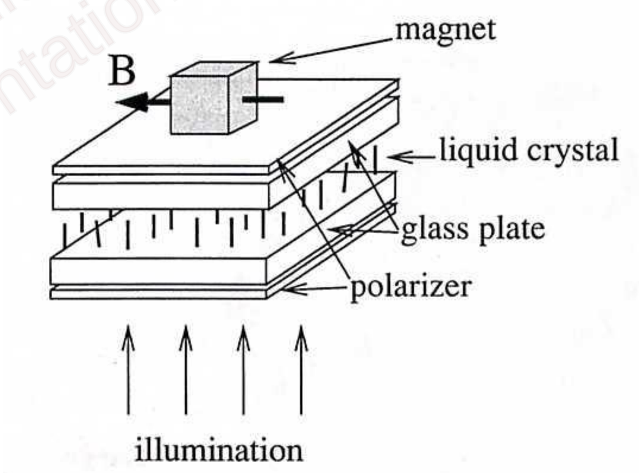
Frederiks experiment

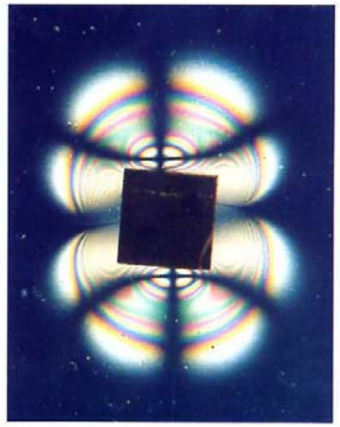
-H-field horizontal
-crossed polarizers
-Newton rings observed

Shown: $H_c d$=const.

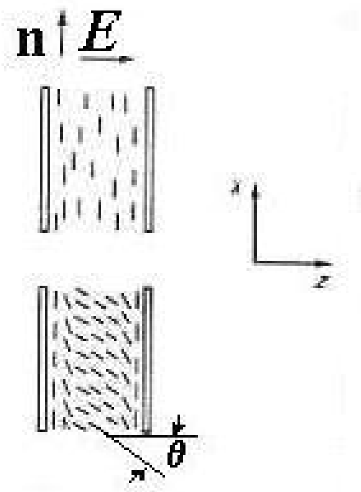
V.K.Frederiks 1885-1944

Modern experiment





Simplest theory, just a balance of the elastic and electric field torques (A. Saupe (1960))



Geometry: $n_x = \cos\vartheta(z)$ and $n_z = \sin\vartheta(z)$.

Frank elastic energy:

$$g_K = \frac{1}{2}[K_{11}(\mathrm{div}\mathbf{n})^2 + K_{22}(\mathbf{n}\cdot\mathrm{curl}\mathbf{n})^2 + K_{33}(\mathbf{n}\times\mathrm{curl}\mathbf{n})^2]$$

Vector algebra:

Splay: $\mathrm{div}\mathbf{n} = \partial n_z/\partial z = \cos\vartheta\cdot(\partial\vartheta/\partial z)$

Bend: $\mathrm{curl}\mathbf{n} = -\sin\vartheta(z)\cdot(\partial\vartheta/\partial z)\mathbf{j}$

$\mathbf{n}\ \mathrm{x}\ \mathrm{curl}\mathbf{n} = \sin\vartheta\cdot(\partial\vartheta/\partial z)\cdot(\sin\vartheta\cdot\mathbf{i} - \cos\vartheta\cdot\mathbf{k})$

Result: $g_K = (K_{11}\cos^2\vartheta + K_{33}\sin^2\vartheta)\cdot\left(\partial\vartheta/\partial z\right)^2$ or

$$g_K = K\left(\frac{\partial\vartheta}{\partial z}\right)^2$$ for $K_{11} = K_{33} = K$

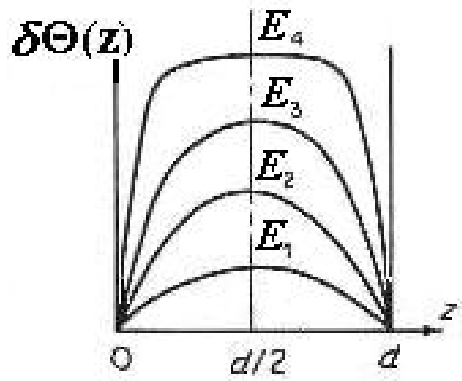
Now, density of electric field energy: $$g_E = \frac{\varepsilon_a(\mathbf{En})^2}{4\pi}$$

$$F = \frac{1}{2}\int_0^d \left[K\left(\frac{d\vartheta}{dz}\right)^2 - \frac{\varepsilon_a E^2}{4\pi}\cos^2\vartheta \right] dz$$

Minimum of F? A variational problem:

Euler equation, general: $\frac{\partial F}{\partial \vartheta} - \frac{\partial}{\partial z}\frac{\partial F}{\partial \vartheta'} = 0$ and particular: $2K\frac{\partial}{\partial z}\cdot\frac{\partial \vartheta}{\partial z} + \frac{\varepsilon_a E^2}{2\pi}\sin\vartheta\cos\vartheta = 0$

Balance of torques: $\xi^2\frac{\partial^2\vartheta}{\partial z^2} + \sin\vartheta\cdot\cos\vartheta = 0$ $\quad \xi = \frac{1}{E}\sqrt{\frac{4\pi K}{\varepsilon_a}}$ E-coherence length



Solution in elliptic functions (A.Saupe, 1960).

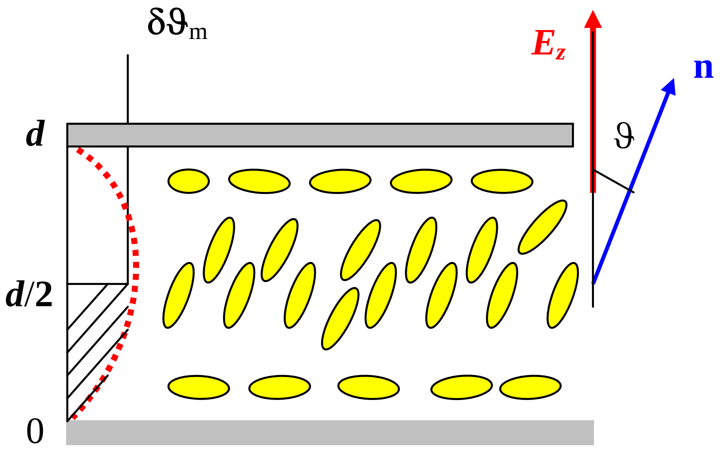
Too complicated?… Try small distortions, $\sin\vartheta \approx \vartheta$, $\cos\vartheta \approx 1$

$$\xi^2\frac{\partial^2\vartheta}{\partial z^2} + \vartheta = 0$$

linear equation with harmonic functions

$\delta\vartheta = \pi/2 - \vartheta = \delta\vartheta_m \sin qz$ with $q = \pi/d$.

After substitution: $-\xi^2 q^2 + 1 = 0$ or $\xi_{Fr} = \frac{d}{\pi}$



Threshold condition: $\pi\xi_{Fr} = d$ or $E_{Fr} = \frac{\pi}{d}\sqrt{\frac{4\pi K}{\varepsilon_a}}$

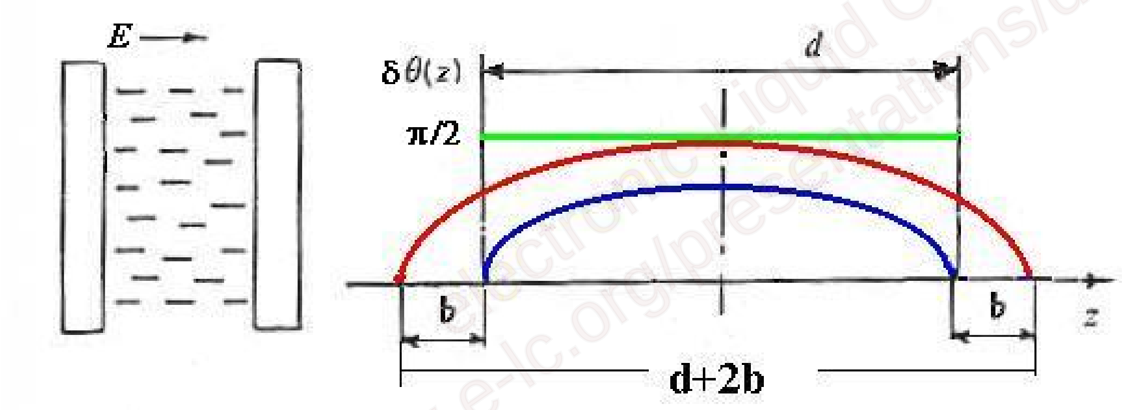
Frederiks experiment: $H_c d$=const

Weak anchoring energy W^s

and new characteristic length $b = K_{ii}/W^s$

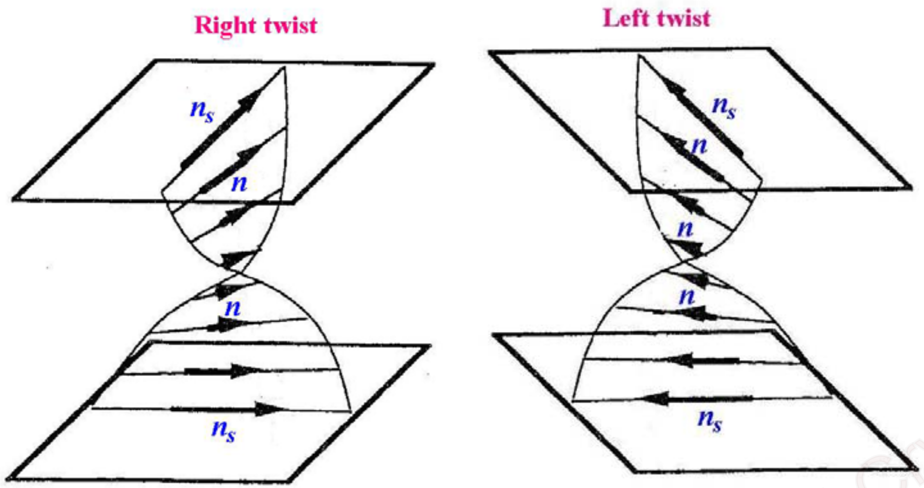
Break of anchoring- new threshold:

$$\pi\xi_{BA} = b$$

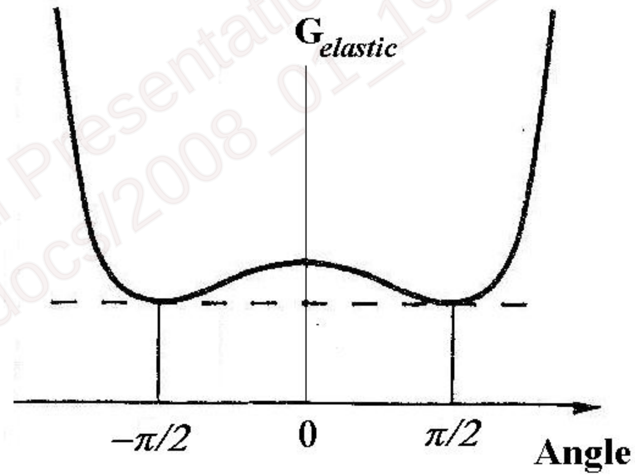


After the break: which way to relax? Frustration: the idea for bistable switching!

The naive idea of bistability for a twisted nematic:



For strongly rubbed plates the twisted structure has lower energy $F_{el}+F_s$

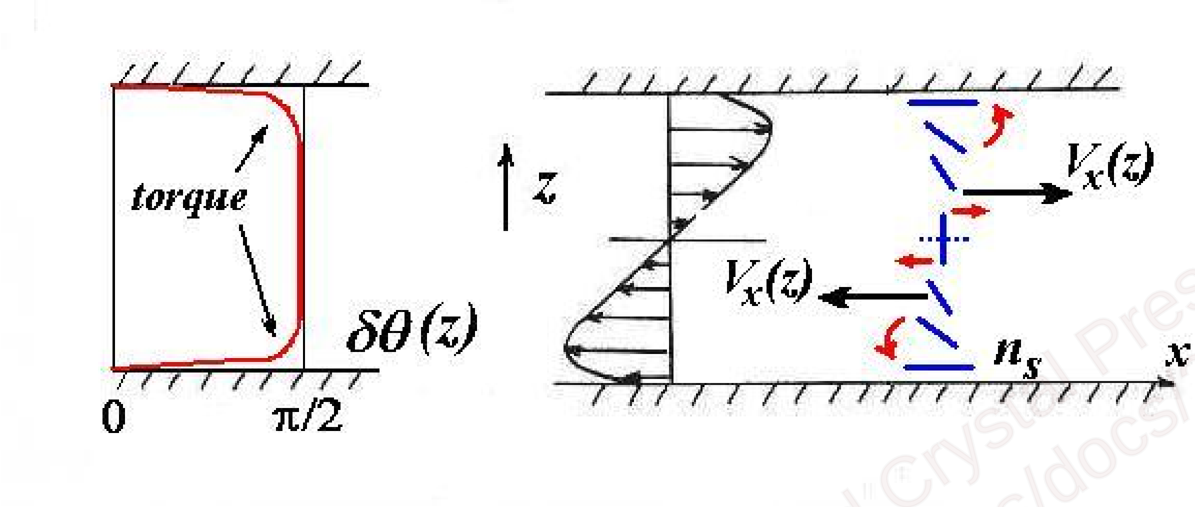


The two structures transmit CPL differently.

But how to force the director select one of them by field application?

First to orient director almost vertically and then to let it relax to one of the two structures using a torque of non-electric nature, e.g. hydrodynamic (D.Berreman, G.Durand, R.Barberi, F.Martinot-Lagarde, I.Dozov, S.Palto)…

Backflow effect:



Important:

Fast relaxation of the director close to the plates creates a flow, which, in turn, drives the director in the middle of the cell

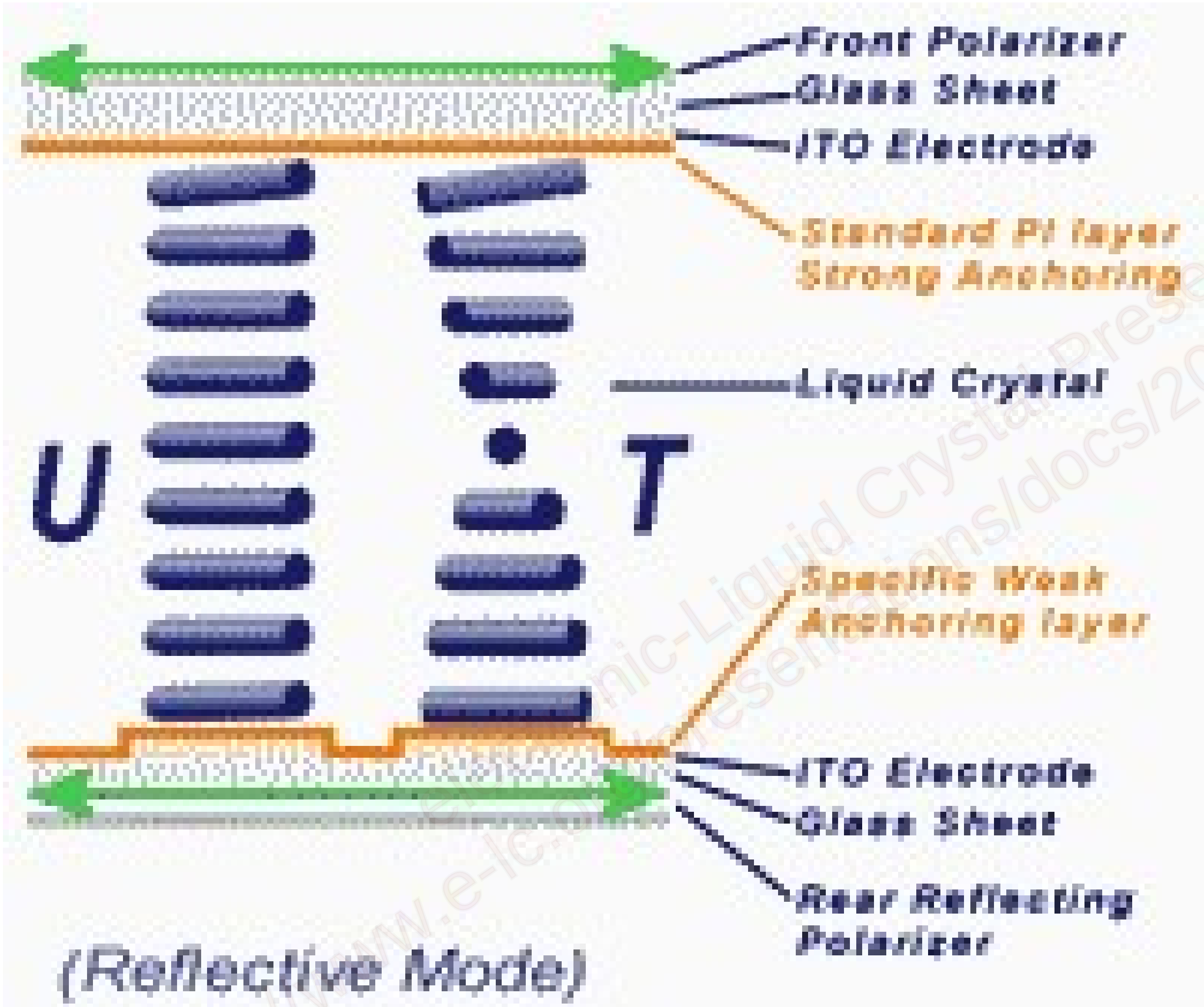
This can be used for the final structure selection

$$\rho \frac{\partial V}{\partial t} = \frac{\partial}{\partial z}\left(A \frac{\partial \vartheta}{\partial t} + B \frac{\partial V}{\partial z} \right)$$ equation of motion for liquid

$$\gamma_1 \frac{\partial \vartheta}{\partial t} = K \frac{\partial^2 \vartheta}{\partial z^2} + \frac{\varepsilon_a}{4\pi} \sin \vartheta \cos \vartheta - A \frac{\partial V}{\partial z}$$ torque balance for the director

A,*B* –combinations of viscosities

Bistable **Nemoptic** display with memory

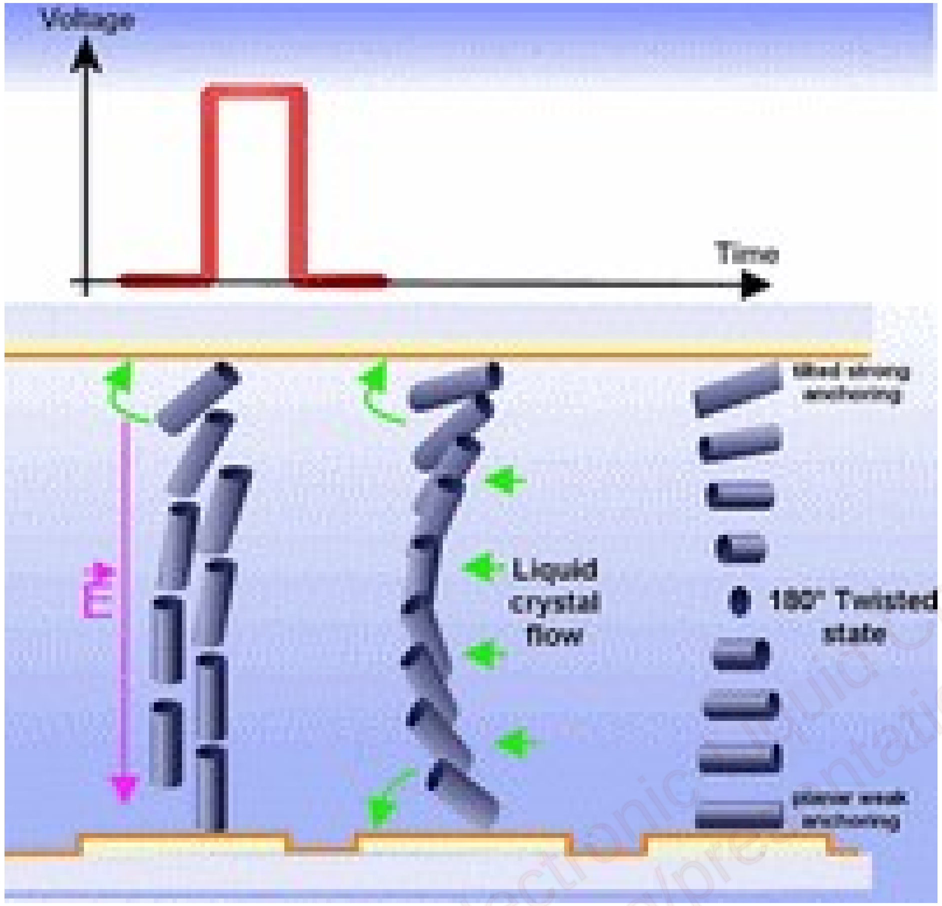


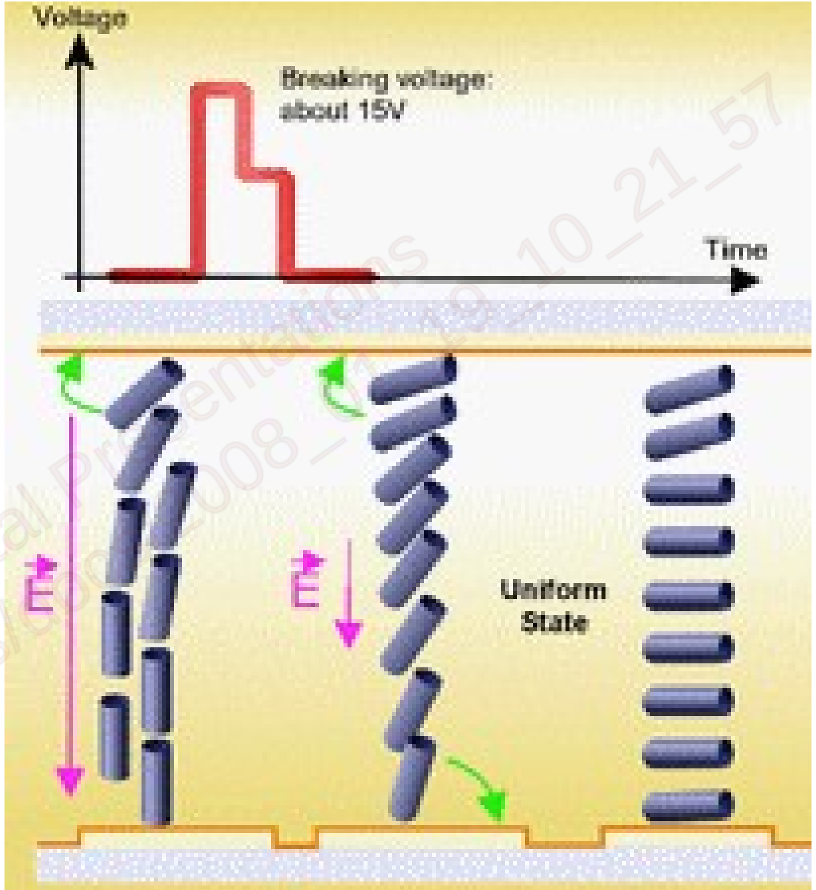
LC has well tuned (weak) chirality

The two structures have similar minima of elastic energy

The director position is different in the cell center

The backflow selects the T-structure during relaxation after the break of anchoring.



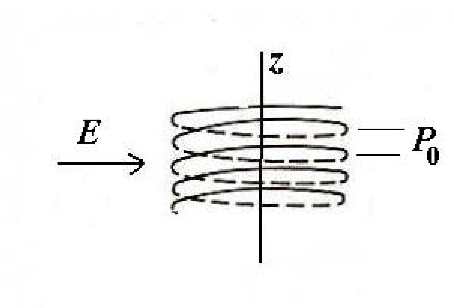


Steep rear edge of pulse causes strong twisting backflow

Step-like edge results in smooth relaxation to uniform state

The result is a beautiful display with memory for energy saving devices, smart cards, electronic paper, electronic posters for the next OLC conferences, etc)

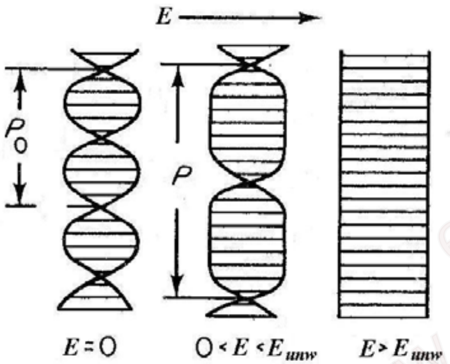
IV. Helix unwinding *(P.G. de Gennes, R.B. Meyer, 1968)*

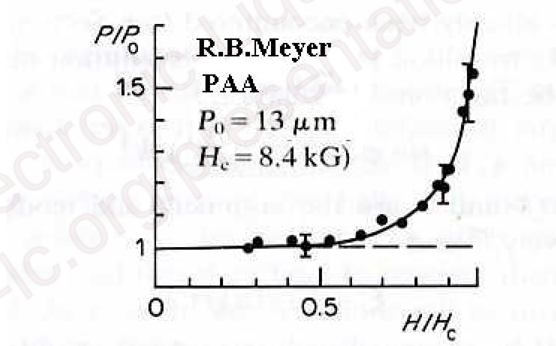


$$g_{Ch} = \frac{1}{2}\left[K_{22}\left(\frac{d\varphi}{d\,z} - q_0\right)^2 - \frac{\varepsilon_a E^2}{4\pi}\cos^2\varphi\right]$$ (infinite helix)

Unwinding threshold: $E_{unw} = \frac{\pi^2}{P_0}\sqrt{\frac{4\pi K_{22}}{\varepsilon_a}}$ or $\pi^2 \xi_{unw} = \frac{2\pi}{q_0} = P_0$

Field dependence of pitch: $P(E) = P_0\left[1 + \frac{\varepsilon_a^2 P_0^2}{2^{11}\pi^5 K_{22}^2} E^4 + \ldots\right]$



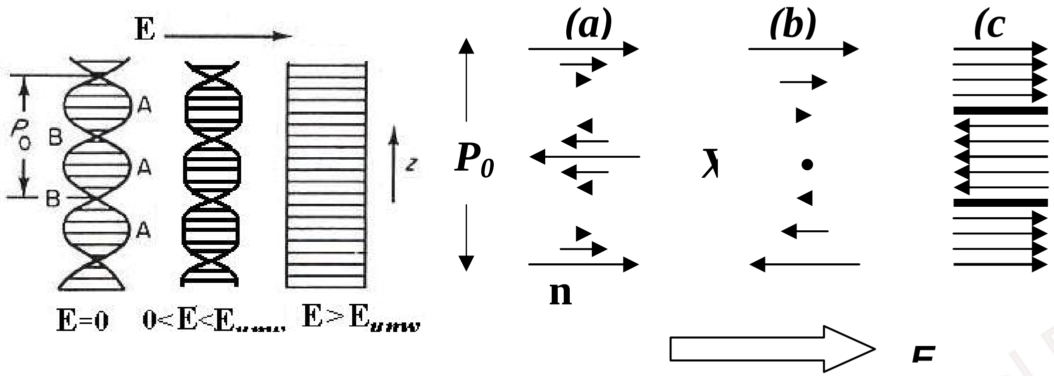


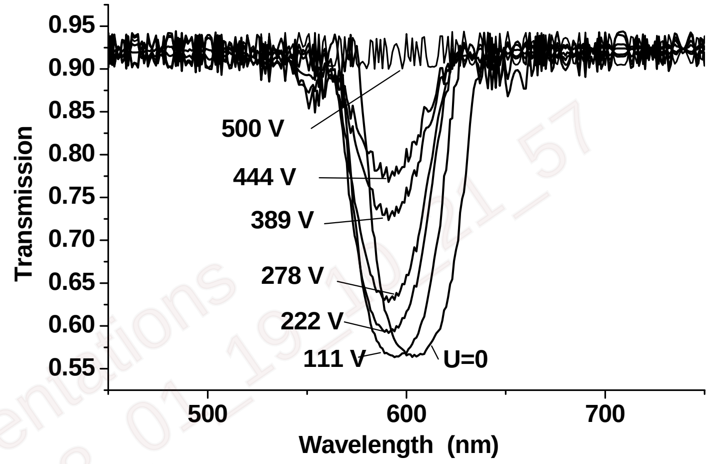
Hopes

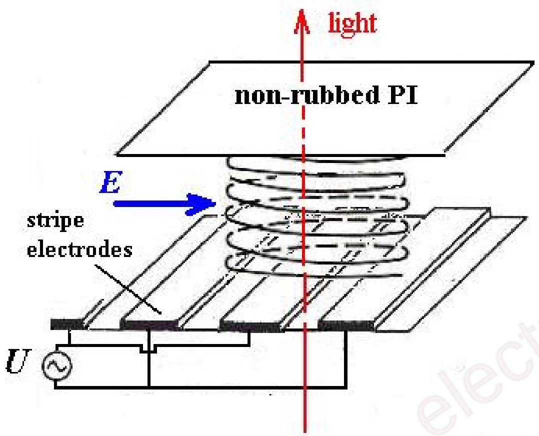
Fast effect for short pitch $\tau = \frac{\gamma_1}{K_{22} q^2}$ $q = 2\pi/P$

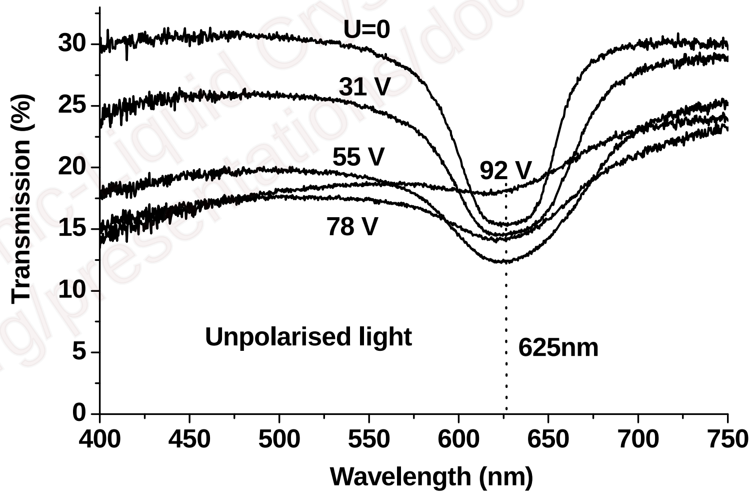
- fast color displays
- field controllable optical diffraction,
- tunable DFB lasers, etc

More realistic situation: modelling and experiment *(S. Palto, L.Blinov 2005)*









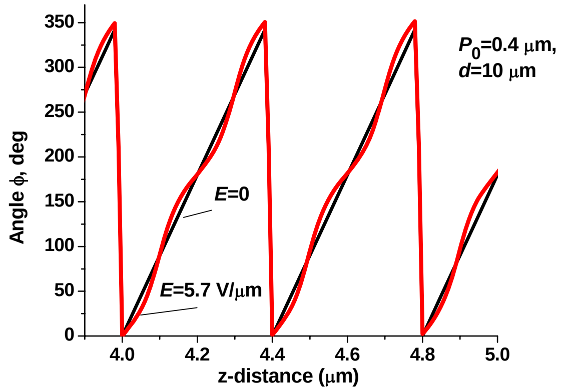
Thermodynamics is not sufficient, there are topological confinements even for infinite helix

The helix can be unwound and wound back only very slowly, via defects

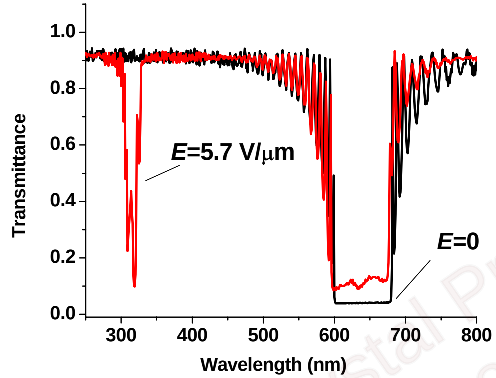
Usually one observe only field induced anharmonicity without change of the period

Field induced anharmonicity and fast display (M.Barnik, S.Palto et al, 2006)

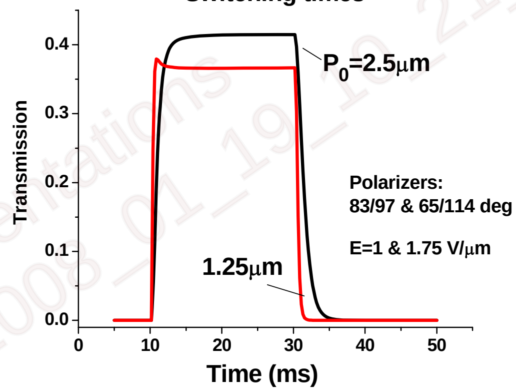
Induced doubing of periodicity



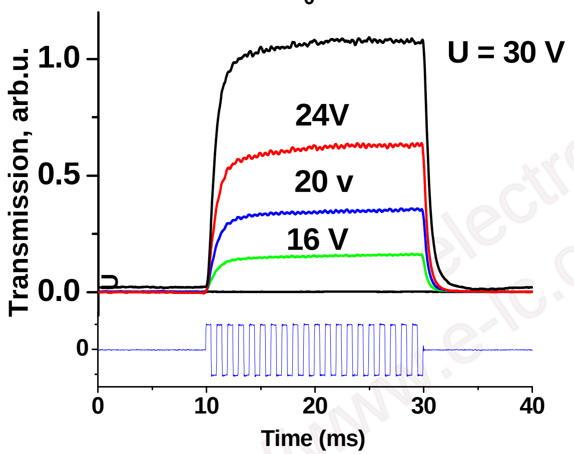
Field induced helix anharmonicty



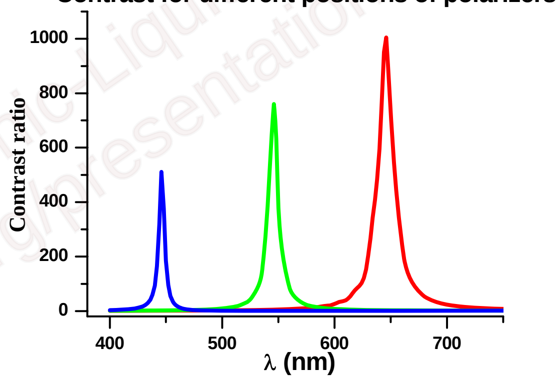
Switching times



Experiment P_0=2.5 μm



Contrast for different positions of polarizers



Results

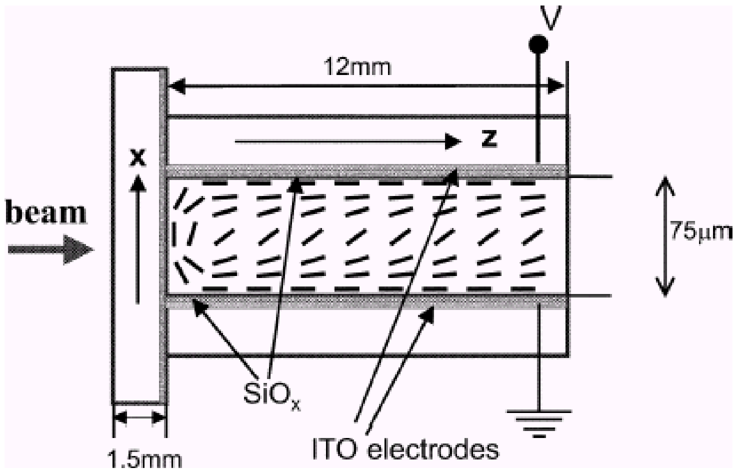
Times: 4 times shorter

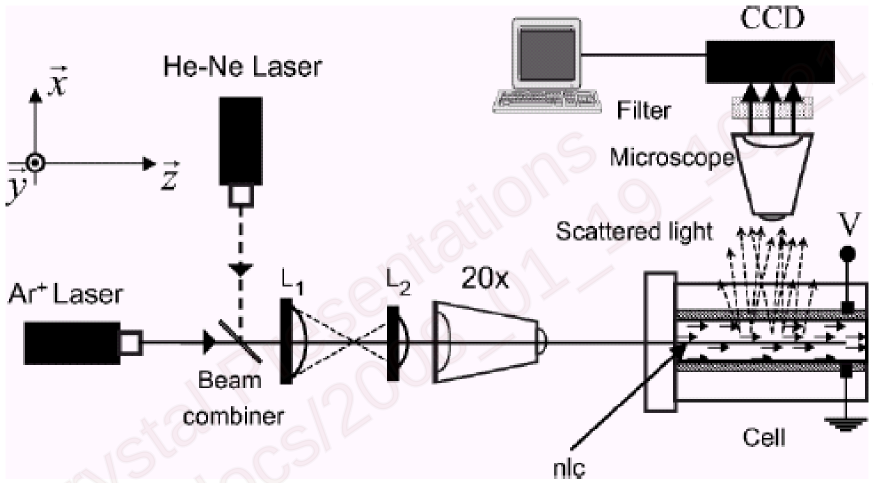
(400 μs-1.5 ms) due to doubling of period of the structure:

$$\tau = \frac{\gamma_1}{4K_{22}q^2}$$

High contrast is solely defined by polarizers

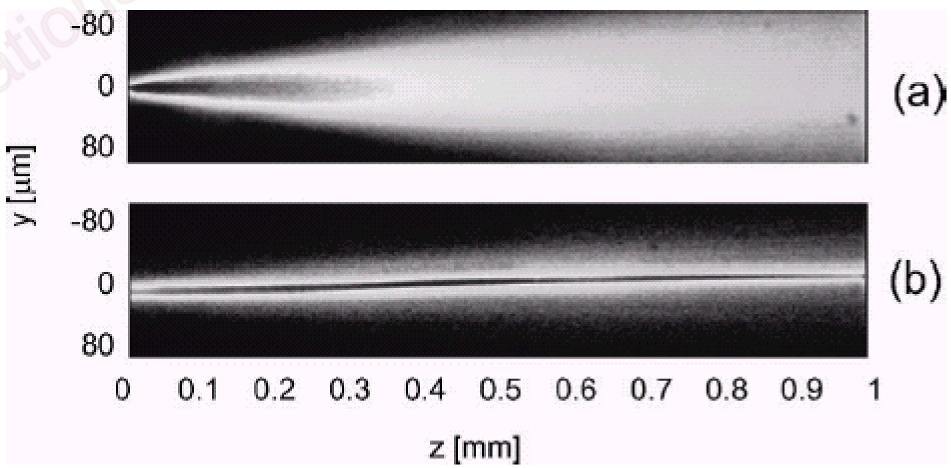
V. Hybrid of electro-optics with non-linear optics: filed control of spatial solitons





XXIII. G. Assanto et al

Idea: To use the non-linear effect of beam self-focusing for compensation of the beam divergence.

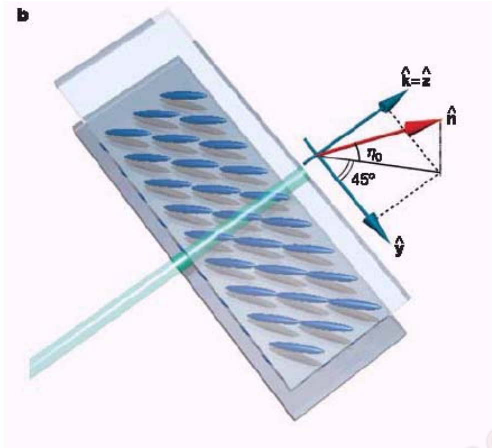


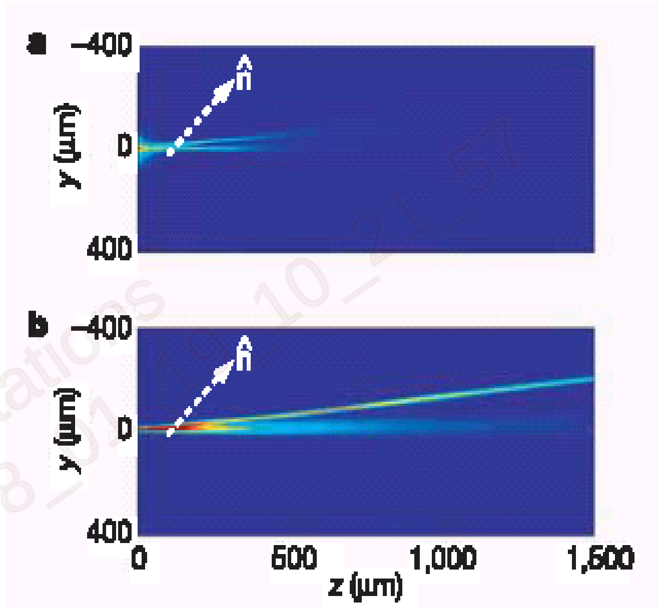
Experiment:
U=1V, *y*- (a) and *x*- (b) polarized beams
IEEE J. Quant. Electr. 39, 13 (2003)

Routing of anisotropic spatial solitons and modulational instability in liquid crystals

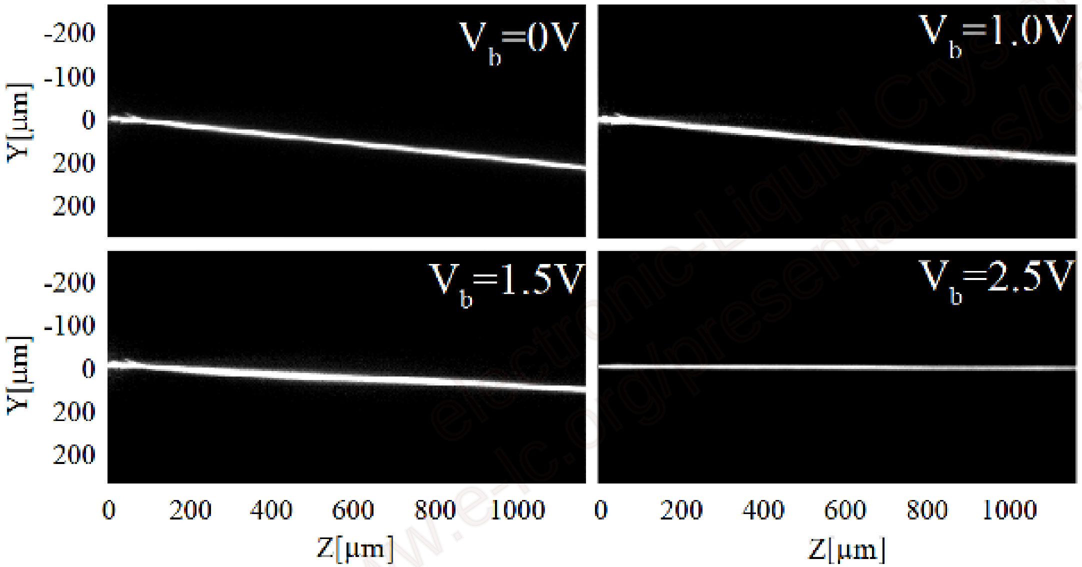
Marco Peccianti[1], Claudio Conti[1], Gaetano Assanto[1], Antonio De Luca[2] & Cesare Umeton[2]

Nature, 432, 734 (2004)





Zero bias and low beam power (a); At higher beam power (b) e-beam generates self-waveguiding soliton



The direction of soliton propagation is controlled by voltage

Take home:

Electrooptics of liquid crystals is mature science with hundreds of effects discovered and understood

Only few effects are used in conventional display technology, mostly based on the different versions of the Frederiks transition

There are serious demands for new effects for future display technology (smart cards, electronic paper, etc.), optics (fast SLM, field controlled diffraction elements, waveguiding devices) and nonlinear optics (laser devices, phase conjugation, routing, etc.).

<u>Acknowledgements</u>: to all my colleagues from the Calabria University and the Institute of Crystallography of Russian Academy of Sciences